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Addressing the Productivity Paradox with Big Data
A literature review and adaptation of the CDM econometric model

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Contents

Tables and figure

Executive Summary

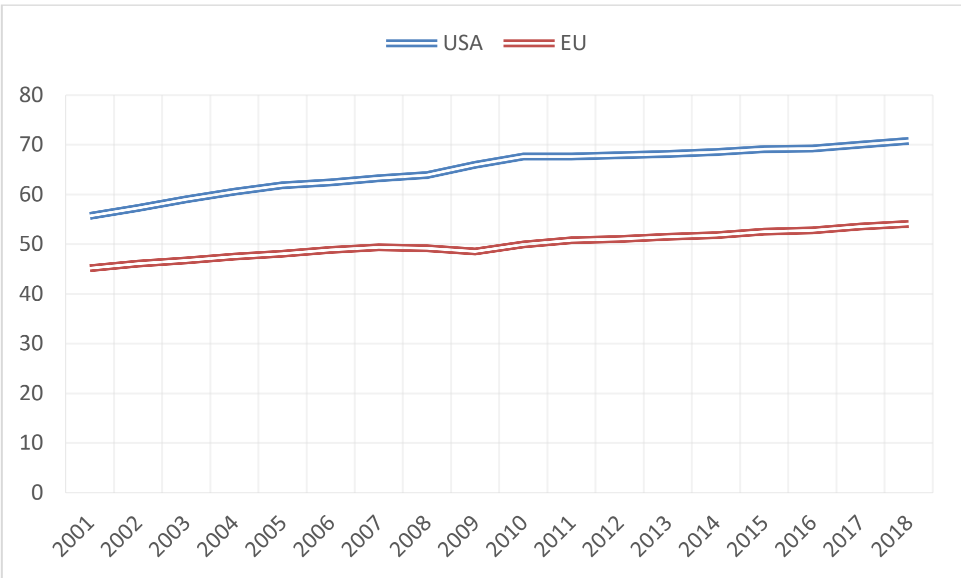
This paper develops the plan for the econometric estimations concerning the relationship between firm productivity and the specifics of the innovation process. The paper consists of three main parts. In the first, we review the relevant literature related to the productivity paradox and its causes. Specific attention will be paid to broad economic trends, in particular the higher importance of intangibles, the increasing importance of knowledge spillovers and servitization as drivers of the slowdown in productivity growth. In the second part, we introduce a plan for the econometric estimation strategy. Here we propose an extended Crépon-Duguet-Mairesse type of model (CDM), which enriches the original specification by the three influence factors of intangibles, spillovers, and servitization. This will allow testing the influence of these three factors on productivity at the level of the firm within a unified framework. In the third part, we build on the literature review in order to provide a detailed plan for the data collection procedure including a description of the variables to be collected and the source from which the variables are coming. It should be noted that we will rely partly on structured data (e.g. ORBIS), while many others variables will need to be generated from unstructured sources, in particular the webpages of firms. The use of unstructured data is a particular strength of our proposed data collection procedure because the use of such data is expected to offer novel insights. However, it implies additional risks in terms of data quality or missing data. Our data collection plan explores the maximum potential of variables that will ideally be made available for later econometric treatment. Whether indeed all variables will have sufficient quality to be used in the econometric estimations will be subject to the outcomes of the actual collection efforts.

1 Introduction

Most economists agree that productivity growth is the engine driving economic growth and welfare increases. In particular in the economic crisis, which held many European countries hostage for extended periods since 2008, as well as a threatened continuation following the SARS-CoV-2 outbreak, economic recovery will depend on gains in productivity. However, the consensus that investments into R&D would be a sufficient condition for achieving productivity growth (Pakes et al. 1984; Bond et al. 2003; Hall et al. 2010) is increasingly put into question (see also Schubert and Neuhäusler 2018). In many countries, R&D-spending increased (Ha and Howitt 2007) while productivity growth actually came almost to a halt (Eichengreen 2015). Syverson (2017), for example, shows that labor productivity growth in the US was 1.3% p.a. for the period 2005 to 2015, after having been more than twice as high in the preceding decennium 1995 to 2004. During the same period, R&D expenditures as a share of GDP rose from 2.4% to about 2.7%.

A further issues, is that productivity growth is even lower in the EU as compared to the US (see Figure 1). Building on the EU-US-productivity gap, Castellani et al. (2019) and Ortega-Argiles et al. (2015) suggest that on average the EU firms are less able to transform R&D expenditures into productivity growth when compared to their US counterparts even when controlling for various structural differences, e.g. in sectoral composition. This may mean that EU firms may have problems in effectively organizing R&D processes and thus in learning from R&D. Thus, instead of catching up, the EU is increasingly falling behind. Macroeconomic estimations using time-series models support that view: Antolin-Diaz et al. (2017) show that productivity growth has fallen from 1% pre crisis to 0% afterwards. The trend growth of real GDP has fallen in the US in the same period by 1 percentage point to 2%, which again is largely attributable to a slowdown in productivity growth. Similar arguments are made by Havik et al. (2014, see also Crafts 2015).

Figure 1: The development of productivity growth in the EU and the US



GDP per hour worked (USD, 2010 PPP) in the period 2001–2018 Source: OECD productivity database.

A number of explanations for the productivity slowdown have been put forward, including issues in current monetary policies (Summers 2014, 2015; Krugman 2014; Eggertsson et al. 2016) or changes in social welfare systems (Glaeser 2014). A more technology-centered perspective has promoted the idea of the so called "secular stagnation" (Eichengreen 2015), which is a supply-side explanation. Secular stagnation as supply side phenomenon builds on the notion of growth accounting, which treat technological progress as the residual in growth that remains unexplained when physical factors, such as labour and capital, are accounted for (compare for example Solow 1988; Mankiw et al. 1992; Barro 1999). The change in the residual equated to technical change can be understood as a measure of total factor productivity (Solow 1956). If, however, technical change is the ultimate driver of productivity growth, endogenous growth theory (Romer 1990, Aghion and Howitt 1990) suggests that rather than generic macroeconomic forces such as government infrastructure investments or monetary policies, changes in how innovation processes unfold should be center-stage. To date, there are few studies dealing exactly with the question of productivity returns to innovation. And for those that exist, the results appear to be more complicated then purely declining productivity returns. Indeed, the secular-stagnation hypothesis has come under attack, with some authors arguing that the depletion of technological opportunities is largely phantasmal (Glaeser 2014). Correspondingly Mokyr (2014) argues that technological opportunities in a large number of industries including computing, materials, and genetic engineering will be continuing in the future. One of the few empirical analyses is provided by Schubert and Neuhäusler (2018), who show for 11 OECD countries that the effects of sector-intramural R&D on productivity are not declining. At the same time, the effects of capital-embodied technological change have dropped to almost zero since the early 2000s, implying elements of technology may indeed play a role even though the story is probably more complicated than simply decling productivity returns of R&D.

This technological view puts the innovation process center stage in explaining the productivity paradox, where the innovation process has undergone important changes since the post-war period. The currently ongoing paradigm of increasing dependence on digital technologies in all parts of the economy encompasses a number of separated but interrelated institutional and managerial changes in how innovation takes place and by whom it is performed. This is described using three mechanisms observed in innovative firms: a higher investment in intangibles (in particular digital ones), a reliance on open networks and related to it spillovers, a greater service component embodied within otherwise standard manufactured goods. We will argue in the following that these mechanisms are likely to have caused attribution and measurement issues with respect to output and inputs.

Investment into intangibles have become increasingly important (Acemoglu et al. 2014). Investment in intangibles results in a number of tangible investment for firms. Nonetheless both the inputs and outputs of this investment may be hard to measure. Haskel and Westlake (2018) provide an insightful discussion of the conditions under which the increasing importance of investment into intangibles may lead to structural declines in the growth of the productivity rates.

Open innovation has become mor widespread. Innovation shifts away from producer innovation to innovation in open networks (Chesbrough 2003; Foss and Saebi 2007; West and Bogers 2017), where innovation not only informed but is also induced by users (Baldwin and von Hippel 2011). Thus, the locus of the innovation process increasingly transcends the boundaries of the firm, because knowledge has become too complex to be mastered within the boundaries of only one firm. At the same time, open innovation may give rise to spillovers, which makes the attribution of returns to innovation e.g. in terms of productivity gains more difficult to measure, assess and attribute correctly.

A final aspect of the shift in the innovation process is servitization (Baines et al. 2009). This means that once stand-alone physical commodities are increasingly bundled with the provision of services. Business model innovation (Zott et al. 2011) has loosened the strict boundaries between the manufacturing of physical commodities and the production of services. This further implies that a larger part of value-added in the manufacturing sector derives from the provision of services. If the service-component becomes more important in manufacturing, it follows that productivity growth relies on the changes in the rendering of this service component. A shift towards a higher share of services in overall value-added may partly explain the decline in productivity growth because the technological potential for productivity growth in services is typically lower (Maroto Sánchez and Cuadrado Roura 2009). One of the reasons is that capital-embodied technological change is less important in services. Another reason is that the value of services may be difficult to disentangle when bundled with physical products. It may further be a source of apparent decline in productivity growth because technological change in services is often much more difficult to measure (Wölfl 2003). Thus servitization may lead to structural declines in productivity growth but it may also imply purely measurement-related downward biases.

In summary, we may conclude that there are a number of mechanisms related to changes in technology that may help to contribute to explaining the slowdown in productivity growth. These include intangibles, open innovation/spillovers, and servitization. However, also because of lack of structured data, there are almost no generalizable results for any of these mechanisms as of yet. Because testing the mechanisms will require leveraging data sources that go beyond standard technology and innovation indicators such as R&D and patents, the project BIGPROD and this work package in particular provides the foundation for extracting data on servitization, open innovation, and the use of intangibles by means of big data approaches.

In specific, this paper provides the information on the following topics. In Section 2, we present an overview of the theoretical literature and in particular the three discussed mechanisms. In Section 3, we present the econometric model, which shall be employed to test the mechanisms. In Section 4, we discuss the potential data we are able to draw from the different sources. In specific, we present an initial proposal of which variables may be gathered from structured data sources (e.g. ORBIS, PATSTAT, etc). Others may only be gathered from scraping company websites, and yet others may be obtained from employing further big data approaches based on unstructured data (e.g. topic modelling).

2 Literature review

In this literature review we will first discuss the technology-centered view of the productivity paradox.We will broadly sketch the state of literature and discuss major technology-related explanations of why productivity may have stagnated. We will move on to argue that the technological centered-view is in need of theoretical refinement. In specific, there are likely to be innovation-related causes of the productivity slowdown. However, they need not necessarily be linked to a depletion of technlogical opportunites. In specific, we promote three specific changes in the innovation process, which may be relevant to explain the productivity slowdown. Introducing these mechansisms serves two goals. First, it allows us to develop structural arguments or hypotheses, which can be tested in later parts of the project. Second, it allows us to delineate the conceptual background necessary to develop the measurement concepts for the three mechanisms.

2.1 The Technology-centered view of the productivity paradox

The Depletion of Technological Opportunities

One of the most prominent arguments explaining the secular stagnation phenomenon which subscribes to a technology-focused view is based on the notion of the decline of technological opportunities stemming from the digital revolution (Gordon 2014, 2015). In essence Gordon argues that the emergence and diffusion of new general-purpose technologies (Gordon labels them as identifiable industrial revolutions, such as electrification) propels economic and productivity growth over a long period of time. However, as the technological opportunities deplete, economic and productivity growth decline too, leading eventually to phases of economic stagnation. In fact, Gordon's point is not so much that productivity growth is currently unusually low but that it was unusually high in the period 1930-1980. Productivity growth is just now returning to normal (Popović 2018). According to Gordon (2014, 2015), the main technology driving productivity growth in recent years was IT, but since IT technology is largely diffused there are only few technological opportunities left to further drive productivity.

One central claim of this view is that the productivity returns to R&D should have declined in general. On a theoretical level, a number of authors have disputed this view or have further refined the hypothesis. Some authors argue for example that digitalization in production and B2B-relations, and that advances in medical, nano- or bio-sciences are likely to enhance productivity growth in the future (Mokyr 2014). Likewise, Brynjolfsson et al. (2017) claim that to the degree there is a productivity slowdown it is largely due to implementation lags. The authors expect that artificial intelligence may bring considerable productivity gains.

The Decline of Capital Embodied Change

A more complex case for slowdown is made by Schubert and Neuhäusler (2018) which shows that while there is no evidence of declining productivity returns to R&D, capital embodied technological change has almost come to halt hold as a driver of productivity growth. Goldin et al. (2020) argue that the slowdown may be due to reduced capital deepening. In-line with Gordon’s view, Schubert and Neuhäusler (2018) and Castellani et al. (2019) argue that the productivity growth that was induced by office and retail digitization in the 1990s and early 2000s is likely to be over and will not return to pre-IT-revolution levels.

A Reduction Innovative Core of Firms

A further explanation for the productivity slowdown relates to the share of innovating firms. In some European countries' innovator shares have dropped to comparably low levels, including for example Germany, Sweden and Austria. Rammer and Schubert (2018) provide evidence that the share of innovating firms in Germany fell from 56% in 1999 to 34% in 2015. Thus, even though overall innovation expenditures are still on the rise, the innovative core of firms is becoming smaller with many firms becoming decoupled from innovation activities. While the reason for the declines in innovator shares is still subject to scholarly debate, it seems reasonable to assume that declining innovator shares are likely to lead to lower rates of productivity growth as well, because the most innovative firms are typically also the most productive ones.

The Mismeasurement of Production

A further explanation of low productivity growth results from an increase in the role of intangibles (see for instance Acemoglu et al. 2014). With firms investing heavily in intangibles; R&D, software, brands, and other intangible assets, changes in measured GDP understates the actual changes in total output (McGrattan 2017). This is because GDP as measured does ot include these varied intangible investments. This mismeasurement is, according to Haskel and Westlake (2018), the primary link between intangible investment and the observed slowdown. Mokyr (2014) and Popović (2018) make a similar point and argue that the methods used to measure productivity growth are more applicable to traditional industries than they are to improvements in consumer product industries, which is particularly driven by what has come be known under the term gadget industry. Gadgets are often not final and finished but are continuously improved also after sale has happened (e.g. mobile communication devices). It implies that traditional ways of measuring productivity rely only on approximating the producer surplus but ignore the consumer surplus, not even speaking about externalized social surplus (Derviş and Qureshi 2018). Essentially, the mismeasurement argument provides a powerful critique of Gordon's secular stagnation hypothesis. Generally speaking, intangibles drive productivity through providing direct input into consumer goods, as well as spillovers to related product segments. An underestimation of the use of the of intangibles or the services rendered by them will therefore manifest in a slowdown in total-factor productivity.

In summary, the technology-focus view on the decline in productivity rates has provided at least four separate explanations of the declines in productivity growth. The first resorts to a decreasing effectiveness of internal R&D expenditures, which is based on the notion that technological opportunities have become depleted over time. The second argues, that capital embodied technological change resulting] from the investment in modern IT infrastructure has become less important. The third claims that the share of innovators has generally become lower, implying that the innovating core of firms has become smaller. Obviously, the first two explanations argue that the lower productivity growth is the result of declining returns to to innovation, while the latter argues that innovation may be too low as compared to the past.

In this work package we attempt to develop an econometric framework which is capable of empirically discriminating between these and further explanations of the causes of the declines and productivity. We regard a solid understanding of the causes as absolutely central, because policy-measures that could effectively address them, may considerably differ from each other. We outline some of the implications for policy in the next subsection and then sketch the structure of an econometric model that allows us to test the explanations against each other.

2.2 The role of intangibles

Research in the domain of productivity is widespread. The number of related scientific publications as of 25th of July, 2020 reaches 268,727 in the Web of Science Core Collection database (1988 - onwards)[1]. About 15% of the publications address the topics of research and development (R&D), technology and innovation (~41k-42k). Approximately 0.12% (n: 313) addresses both the theme of intangibles and R&D, technology and innovation activities together. The relatively low share of research on intangibles does not denote insignificance, yet reflects the heavy data burden of filling the missing piece of accounting for intangibles in the innovation-to-productivity puzzle (Corrado et al. 2013; Bartelsman et al. 2017).

Our aim is to review the literature to understand better how accounting for intangibles might enhance capturing the value of R&D, technology development, and innovation activities in terms of productivity growth. By doing so, we aim at detecting how data and indicators on intangibles could be defined, collected and constructed using web scraping techniques on firms' websites and be analyzed using big data techniques. We stress the potential importance of accounting for and incorporating intangibles in productivity measurement, as well as interactions among them, considering for instance the complementarities between information and communication technology (ICT), skills training and intangible investments in managerial ICT. Various mechanisms through which varieties of intangibles play an important role in influencing firm performance are scrutinized below.

We have argued that intangibles may cause measurement challenges for productivity. At the same time, intangibles represent key components of the knowledge of firms. They are therefore crucial to their performance (Marrocu et al. 2012). For instance, the lower the intangible asset intensity is, the lower are the barriers to be easily imitated for a firm (Zhang et al. 2014). The role of creating, utilizing and sustaining varieties of intangible capital in strengthening a manufacturing firm's long-term competitive advantage is emphasized by scholars. In other words, competitiveness requires the productive use of intangible capital and assets (Phusavat et al. 2011; 2013).

From a theoretical perspective, intangibles relate to the creation and utilization of varieties of not only classical capital, e.g. financial capital (e.g. via in house mission and vision related investments, public finance) and classical physical capital (e.g. organizational structural capital, enterprise resource planning (ERP) systems, combined technology and ICT use, product diversification), but they also relate to varieties of neo-capital, such

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[1] [1] Query # 1| n: 268,727 TOPIC: (productivity) OR TITLE: (productivity) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years Web of Science Core Collection Thomson Reuters
Query # 2 | n: 41,741 TOPIC: (productivity) OR TITLE: (productivity) Refined by: TOPIC: ("research and development" OR "R&D" OR "research and technology development" OR "technolog*" OR "technology development" OR "innovati*") Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years Web of Science Core Collection Thomson Reuters
Query # 3 | 313 TOPIC: (productivity) OR TITLE: (productivity) Refined by: TOPIC: ("research and development" OR "R&D" OR "research and technology development" OR "technolog*" OR "technology development" OR "innovati*") AND TOPIC: (intangible*) Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, ESCI Timespan=All years Web of Science Core Collection Thomson Reuters

as human (intellectual) capital at the employees and managerial level, social (business-to-business, e.g. Gopal 2018), business-to-customer, business-to-network relational) capital, cultural capital (corporate social responsibility, corporate digital responsibility, vision, mission, norms, standards) and geographical capital (e.g. eco-system, natural, public policy, internationalization). Utilization of varieties of intangibles can increase performance and competitive advantage of firms, industries and regions.

Moreover, interactions and potential time lags among these varieties of intangibles are also deemed influential for enhancing the precision of productivity research and measurement. These include human capital and cash-flow appropriability (intangibles and time lag) (Kogan and Papanikolaou 2019); better managerial practices, innovative activities (interaction) and returns (time lag) (Nemlioglu and Mallick 2017). In the following subsection, varieties of intangibles and relevant indicators are scrutinized and listed.

Intangibles relating to classical (financial, physical) capital

Intangible financial investments relate to R&D, selling and general administrative expenses (SGA) and other intangibles in marketing investments and activities (Higon et al. 2017; Chen 2018; Mishra and Ewing 2020). Edquist (2011) also emphasizes the investments in intangible assets, such as R&D, design, and advertising. From a financial capital perspective, the availability of public financial capital funds, either as loans and/or tax credits at the supply side or public procurement instruments at the demand side, is important for the value of intangibles. For instance, economic values of biotechnology intangibles are affected by country and sector risks and public financing (Erbas and Memis 2012), as well as intangibles in certain industries, e.g. biopharmaceutical industry (Huang et al. 2011). The source of R&D funds when disclosed transparently and incorporated into the valuation of intangible assets makes intangibles attributable to research and development activities (Billings et al. 2004) .

Intangible and classical capital are complements. For example, organizational structural capital (de Castro et al. 2009a, 2009b) and internal knowledge capital (Marrocu et al. 2012) relate to a very crucial role in shaping a firm's complementary competences, which can favour the success of an innovative business model configuration (Cucculelli and Bettinelli 2015). This includes utilizing the combined use of non-ICT technologies with ICT technologies, including hardware, software, netware (Lankauskiene 2016), and the use of ICT with increased employee skills and human capital formation (Moshiri and Simpson 2011). Although competencies are captured more easily and the relation between ICT and Total Factor Productivity (TFP) is expected to be positive, it can have long time lags of many years (Edquist and Henrekson 2017a). Likewise, macroeconomic productivity revivals may in part reflect the contributions of intangible capital accumulated in the past (Brynjolfsson and Hitt 2000). Other scholars e.g. Basu and Fernald (2007) also agree that ICT as a general purpose technology suggests that measured total factor productivity (TFP) may rise in ICT-using sectors (reflecting either unobserved accumulation of intangible organizational capital (Knott et al. 2003); spillovers; or both), but with a long lag (Basu and Fernald 2007). ICT has an intangible aspect to itself, such as information system (IS)-related processes, IS-related process improvements and their impact on firm performance; e.g. in software sector's public capability maturity model (CMM) level transition announcements as a subset of standardisation and certification of intangible and physical capital (Morris and Strickland 2008) are deemed important in improving productivity (Aerni 2007), which is a statement in line with increasing the productivity of physical investment in R&D processes with intangibles (Lin 2012).

Intangibles play an important role in product diversification, e.g. the inventions of new processes and products (Marrocu et al. 2012). Product diversification is relevant for domestically consumed products, exported products, new products, and even traditional products (Tian 2007). Intangibles, on the other hand, also consist of the innovations which might not be patented (Haskel 2015). Thus, we observe investments in intangibles such as brand equity, architectural and engineering designs, and increasing demand for trademarks and design rights (de Rassenfosse 2017). Intangible resources are thus the most distinctive firms' assets in local and global competitive environments, not only in manufacturing but also, and especially, in service businesses (Zakery and Afrazeh 2015).

In addition to firm size, division of organizational departments and dedicated desks (e.g. production, quality management, sales and marketing desks), and the division of labor among humans and machines with the advance of technology, are also evaluated as important during the creation of intangible assets in Industry 4.0 (Lobova et al. 2019). Maximising productivity benefits from investments in ICTs requires complementary investments in new organisational structures, employee training, and other intangible assets (Chen et al. 2016). Linking firm knowledge to productivity via three characteristics of firm knowledge namely, knowledge capital, knowledge diversity, and knowledge relatedness may explain a substantial share of the variance of firm productivity. For instance, knowledge relatedness matters because it can lower coordination costs between heterogeneous activities of the firm (Nesta 2008). Presence of such intangible effects also inform public and private policy in a way that business decision makers and policy makers may consider raising not only ICT investments (e.g. enterprise information technologies (EITs)) but also the development of intangible capital related to these investments (Li and Wu 2020; Sarkis and Sundarraj 2006; Battisti et al. 2015). In short, the value of intangible capital is positively influenced by innovation, organizational learning, knowledge management, and self-directed learning (Phusavat et al. 2013). In addition, investments in and utilization of digital systems can be useful in assessing the relationships of firms, industries, regions and nations; and if digital connectivity aims at reaching common goals, it can be used to monitor and asses local and global intangible benefits (Coles et al. 2018).

Intangibles relating to human capital

The interactions between varieties of technological capital mentioned in the earlier subsection and its interaction with firm-sponsored employee training are also important (Ballot et al. 2001). From a human capital perspective, productivity of organisational processes relies on the availability of knowledgeable human resources, a subset of intellectual capital. This starts with human resource management in firms in attracting, employing, training and retaining qualified and knowledgeable personnel. Continuous workforce training and human capital formation through the general education system are different processes (O'Mahony 2012). Continuous workforce training can lead to the creation of different and distinct qualified products and services, reducing costs, increasing creativity, competitiveness, and the productivity of the firms (Atashi and Kharabi 2012). Investment in employee skills (Evangelista et al. 2015; Marrocu et al. 2012) as an investment in training of employees also generates increases in terms of future intangible value of the firm (Zambrano et al. 2012). In this domain, health support to human capital is also included in health capital investments which positively affects firm value and overall productivity (Holland 2017). Longitudinal career history data are additionally used to trace the flows of these knowledge workers over time. They are especially important for detecting the sectoral shifts, with a particular focus on the knowledge-intensive service sectors (Tomlinson 1999). Intellectual capital is also evaluated by using occupational data and information when available e.g. in Finnish linked employer-employee data for the 1997-2011 period (Piekkola 2016).

As a function of the quality of human capital, qualifications of the board of directors have also an influence on productivity, strategic long-term orientation of companies, innovative behavior of companies, foreign investments and corporate networks (Shakina et al. 2017). Managerial interpretations are needed for human capital control and reward systems as well as for strategic management via the definition of visions and missions (Epure 2016). These aspects stress the importance of intellectual capital management at the firm level with a key role of top managers for improving intellectual capital management (Wu et al. 2006) and intangible resources in performance improvement by managers. Firm managers, in this sense, are called to pay more attention to the strategic positioning that ICT provides for firms rather than only enhancing the operational effectiveness (Ong and Chen 2013). In this regard, scholars incorporate corporate goals for ICT and management practices as key determinants of realized IT payoffs (Tallon et al. 2000). Value realization from ICT depends on time-consuming investments in organizational change and results in new, often intangible, organisational structural assets in terms of models of ICT business value generation and managerial practices (Gregor et al. 2006). ICT intangibles extend to capitalized software, all purchased and internally developed software, other internal ICT services, ICT consulting, and ICT-related training (whether or not it is capitalized by the firm) (Saunders and Brynjolfsson 2016).

In certain sectors, the importance of human (intellectual) capital, both at employee and top manager levels, becomes even more visible. In the healthcare sector, intangible resources such as clinical skills, knowledge, expertise, experiences, competencies, doctor-patient relations, doctors' and hospital's reputation may be more central than physical resources like physical assets (Hamzah et al. 2017). Once employee training is coupled with enterprise information systems, the organisation may then produce intangible outputs such as health (Ayal and Seidmann 2009). ICT capabilities are based on distinct measures of human resource practices, management practices, internal IT use, external IT use, and internet capabilities. Thus, ICT and connectivity dimensions are also relevant to understanding intangibles. Positive experiences are enabled by the digital and performing arts. The full measurement of these benefits can help create a better account for human capital related investments, and thereby demonstrate higher potential productivity contribution (Crowley and McDonald 2015).

Intangibles relating to social (relational) capital

Intangibles play also a big role in social capital. The social capital dimension involves internal and external aspects. Internal to the company there are needs such as training and mentorship. External to the company there are business-to-business, business-to-network, and research and development alliances, and marketing alliances (Tuli et al. 2010). These intangibles play a big role in ultimate success of the firm, including demonstrated impacts through stock returns (Angulo-Ruiz et al. 2018). Such intangibles enhance marketing investment and activities (Mishra and Ewing 2020), product image (Marrocu et al. 2012), brand capital, and interactions between customer capital and innovation capital (Bayraktaroglu et al. 2019).

Especially in the tourism sector, customers are important. A full examination of the customer capital interface incorporates service complexity (SC), customer interactions, customer channels, and customer loyalty (CL) as inputs. Outputs include repeated customers, referred customers, and willingness to pay. A positive customer experience is an important component of service productivity (Scerri and Agarwal 2018). The positive effect of client relationships on innovation, established alliances and companies' reputations is also shown by de Castro et al. (2009a; 2009b). Customer capital also consists of trademarks and advertising (Bontempi and Mairesse 2015).

Business suppliers in B2B settings are increasingly building a portfolio of multiple types of ties with individual customers (Tuli et al. 2010), targeting joint productivity gains as return on relationships (ROR) (Gronroos and Helle 2012). In this setting, partner-based technologies harnessing informational and relational resources that drive overall performance in supply chains and business alliances are also important intangibles (Richey et al. 2008; Chang 2013) due to horizontal spillovers and the impact of backward and forward vertical spillovers from services and manufacturing sectors (Orlic et al. 2018). Investments in organisational capital increase productivity of not just the investing firm but could also create spillover to other firms-similar to investments in research and development (Chen and Inklaar 2016) and to domestic value added in global value chains (Vrh 2019). Interactions with SOEs and public procurement bodies are also part of social relational intangibles.

Intangibles relating to geo-locational capital

This social-relational and contextual embeddedness of intangibles introduces the geo-locational capital, an eco-system capital (location in terms of technological and human endowments, as well as for the regional infrastructures and settlement structure (Marrocu et al. 2012)). Firm location plays a critical role in the global competitiveness of companies (Shakina et al. 2017). The positive influence on firms' productivity can be exerted by internal knowledge capital and by intangible assets available in the regional economy (Marrocu et al. 2012). Such findings highlight the importance of public and private policies which are designed to stimulate the accumulation of intangible capital stocks internal to the firms, and support the development of an adequate knowledge system at the regional level (Marrocu et al. 2012; Park 2015; Peiro-Palomino 2016; Kaasa 2018). However, industry-level endowment with regard to intangibles may contribute more to firm performance in comparison to firm-level endowments in the context of the transitional economies (Molodchik et al. 2019).

For instance, for hotels and the tourism industry in Spain, this would be more visible, such that both the intangible capital of the company and that of the region in which the company is located are considered as determinants of productivity (Rico et al. 2019). Methodologically, recent versions of the neoclassical models involve spatial weights and convergence clubs[2]. These models use new economic geography ideas such as core-periphery models, and the innovation system approaches (Harris 2011). Intangible inputs like research and development (R&D) expenditure, human capital (HK) and social capital (SK) are incorporated in such quantitative analyses (Marrocu and Paci 2010).

[2] The convergence club hypothesis relates to the idea that the economies which are similar in their structural characteristics may not converge to the same steady state equilibrium if the initial conditions are not similar (Azariadis and Drazen 1990; Galor 1996; Bartkowska and Riedl 2012)

From an acquisition and intangibles perspective, foreign ownership may also enable target firms to obtain better access to external finance. So, this would display lower dependence of target firms on internal investments and cash savings on the availability of internal funds (Stiebale and Wessner 2020), and this could increase domestic value added in global value chains (Vrh 2019). In this financial sense, intangibles also relate to the availability of regional and national public policy funds and the quality of the institutional environment (Marrocu et al. 2012). E.g. scholars document a robust correlation between UK public-sector financed R&D disbursed via research councils and the market sector total factor productivity growth (Haskel and Wallis 2013). Certain framework policies (e.g. circular economy, digital economy) which have a certain regional and national aspect to them increase the creation and use of intangible resources (knowledge, intellectual capital) (Nedelea et al. 2018). Policies influence the intellectual capital (IC) profile of industrial sectors in transition (O'Connor et al. 2015). Main policy directions and the key areas of business support in this geo-locational regard involve the business environment, skills upgrading, network infrastructure, trust infrastructure, digital products and information services, intangible investments and assets, information, government and/or administrations on-line (Gatautis and Vitkauskaite 2009).

As a result, the notion of the fuzzy firm emerges, where traditional corporate boundaries have become amorphous, with the result that the firms require new valuation methodologies due to their intangibles (Johnson et al. 2002). In such intangibles settings, there might be significant spillovers to productivity from public sector R&D spending on research agencies and higher education (Elnasri and Fox 2017). Digital business support areas thus extend to key dimensions of business (functional, sectoral, and regional/spatial) on three distinct levels (micro: the level of the firm, meso: the level of the region, and macro: national/international) (Gatautis and Vitkauskaite 2009).

In this sense, internationalization, especially for innovative firms eager to capitalize on their technological advances, represents a springboard for rapid international expansion of sales (Filatotchev and Piesse 2009). For instance, in industries characterized by high levels of intangible assets such as technologies or brands a converted wholly owned subsidiary may outperform continuing joint ventures (Chang et al. 2013). From an organizational learning perspective, as entry tenure of foreign firms in an industry increases, domestic firms can learn from foreign firms over time and improve their productivity (Zhang et al. 2014). For instance, sales, productivity, and tangible as well as intangible assets of the acquiring firms may increase substantially after M&A transactions (Edamura et al. 2014). Internationalisation theory of FDI postulates that multinational firms transfer a range of intangible proprietary assets to their affiliates (Girma et al. 2007; Bridgman 2014), with a note that the transfer of intangible assets from foreign firms to domestic firms are difficult (Salis 2008). There is also evidence that the multinational price premium (export prices across firms) is significantly correlated with the knowledge-based intangible assets within multinationals (Ge et al. 2015). Host country equity participation in foreign firms is consistent with higher unconditional productivity spillovers to domestic firms (Marcin, 2008). Having noted that, in the internationalization and spillover debate, firm size is also an important control factor (Fukao 2013).

Thus, finally this geo-variety has a time dimension: importance of intangibles can increase over time (Clausen and Hirth 2016). These distinctive evolutionary dynamics of intangible capital as opposed to that of physical capital can help mitigate the negative impact of temporary uncertainty shocks on production and can serve well to explain the value premium with modest assumptions (Ahn 2019). Higher intangibles may be more beneficial when combined with R&D activity (Nemlioglu and Mallick 2017). Also, firms with better managerial practices and innovative activities exhibit a positive effect of higher leverage (Nemlioglu and Mallick 2017). Financing frictions impact the increasingly important yet understudied intangible corporate investments that drive innovative activity (Borisova and Brown 2013; Zhao et al. 2019). E.g, in the manufacturing sector are found to relate to age, firm size, R&D intensity, advertising intensity (Irfan et al. 2016), due to their impact on market capitalization or acquisition prices in M&A transactions (Clausen and Hirth 2016). Internationalisation also has an influence on corporate physical and intangible investments, cross-border decisions, and financial policies (Gu 2017). In terms of labour productivity, it can be predominant due to the intangible assets introduced by foreign firms, rather than simply the fixed capital investment associated with FDI (Barrell and Holland 2000).

Intangibles relating to cultural capital

In the cultural capital dimension, intangible resources consist of norms, values, and goodwill, in addition to other resources such as patents, business and human resources (Lai et al. 2015). Corporate social responsibility (CSR) activities are one of the mechanisms that can create intangible assets that provide firms a competitive advantage (Padgett and Galan 2010). The strategic mission and vision of companies relies on the presence and utilization of socio-technical value-based intangibles (Shakina and Barajas 2016). In this regard scholars also incorporate corporate goals, e.g. for the ICT vision and mission as well as management practices, as key determinants of realized ICT payoffs (Tallon et al. 2000).

Measuring intangibles and productivity paradox

The human-centric (e.g. employees, managers), social (e.g. multiplicities of businesses, networks, markets) and embedded (geographical producer-user eco-systems) mechanisms through which the intangibles listed above become operational have a direct influence on firm level operations, potential competitiveness, performance and productivity. Accounting for varieties of such intangibles can yield more precise estimates for productivity measurement at the firm level. Shortcomings in the treatment of, for instance, intangible investments in firm accounts would imply that there is no adequate statistical data collection and data for overall research and innovation activities of the firm which abide other economic activity data (Jensen and Webster 2009). As a consequence, productivity analysts in general rely on R&D, technology development and innovation proxies, which are not sensitive to intangibles, derived from administrative and survey data (Jensen and Webster 2009). Intellectual capital, customer capital and other intangible assets as well as the use of accounting information on intangible investments are crucial to find precise effects of intangible assets on performance and productivity dynamics.

However the measurement of intangibles even at the micro-level remains very challenging. Correspondingly, intangibles measured from company expenses seem to play a limited role in productivity analysis due to the lack/quality of the data (Bontempi and Mairesse 2015). Thus, filling in missing pieces of the innovation-to-productivity puzzle has a heavy data burden (Bartelsman et al. 2017), and this requires special attention to incorporating intangibles in productivity measurement efforts.

The unavailability of data on intangibles at the micro-level has also a negative impact on productivity measurement at the aggregate level. At the aggregate level, growth accounting methods show that the failure to account for line items such as continuous training leads to an underestimation of the impact of human capital on output growth in the EU (O'Mahony 2012). Likewise, scholars stress that the mystery of Total Factor Productivity (TFP) is likely to remain as long as such measurement errors persist (Oulton 2016). Suggestions exist for possible changes in the national accounts, including the inclusion of multifactor productivity measures in the production account, changes to the definition of output for certain financial services, expanded coverage of intangible assets, capitalization of e.g. military equipment, inclusion of consumer durable goods in measures of saving, imputation of a rate of return to fixed assets used for nonmarket production, reconsideration of sectoral boundaries, and modification of the definition of capital transfers for capital gains taxes (Moulton 2004; Lynch and Thage 2017). Such improvements enable a better measurement and interpretation on the existence of the productivity paradox.

The importance of intangibles for labour productivity growth, and thereby, the necessity to incorporate intangibles into today's national accounting frameworks in order to depict the levels of capital investments being made in European economies more precisely and correctly is an important challenge for productivity research (Roth 2019). Varieties of intangibles (e.g. computerized data and information (digital assests); knowledge assets, employee and managerial skills; innovative and administrative business designs and models, and economic and market competencies) must be incorporated into productivity research. Published macroeconomic data traditionally exclude most intangible investments from measured GDP (Corrado et al. 2009). The Standard National Accounts treatment of most spending on knowledge or intangible assets is as intermediate consumption (Marrano et al. 2009). Thus, they do not count as either GDP or investment; treating such spending as investment affects key macro variables, namely, market sector gross value added (MGVA), business investment, capital and labor shares, growth in labor and total factor productivity (TFP), and capital deepening (Marrano et al. 2009).

A complete accounting of intangibles requires changes to both the input as well as the output of growth accounting frameworks. According to scholars, the incorporation of intangibles into the growth accounting frameworks can take some of the luster off the performance of labor productivity (Oliner et al. 2008; De 2014). As an example, Swedish TFP growth, one of the highest among OECD countries, is reduced substantially when investment in intangibles is included in the growth accounting analysis (Edquist 2011). Not only investments in intangibles but utilization and temporal interactions among them are important. In this regard, the introduction of intangible investments and non-neutral technological change with respect to producing intangible investment goods, services and networks, embedded in ecosystem are deemed beneficial (McGrattan and Prescott 2010).

2.3 Open innovation and knowledge spillovers

It is well-known that knowledge has the property of a public good that is being non-rival and non-excludable. Knowledge can be used at the same time by several people (non-rivalry), and its use by one party does not preclude the use by others (non-excludability). In other words, knowledge can easily spill over from who invested in producing it to others. Nelson (1959), focusing on investments in basic research, claimed that those investments are “likely to generate substantial external economies” (pp. 302). Arrow (1962) argued that the existence of spillovers might lead to sub-optimal R&D investments: “information is a commodity with peculiar attributes, particularly embarrassing for the achievement of optimal allocation. In the first place, any information obtained, say a new method of production, should, from the welfare point of view, be available free of charge (apart from the cost of transmitting information). This ensures optimal utilization of the information, but, of course, provides no incentive for investment in research.” (pp. 616-617).

Knowledge spillovers are seen as an externality according to which agents investing to produce new knowledge benefit also others (Breschi and Lissoni 2001)[3]. Then, spillovers of knowledge across agents need to be taken into account when considering the impact of R&D investment on the individual productivity of each agent. In other words, “the level of productivity achieved by one firm or industry depends not only on its own research efforts but also on the level of the pool of general knowledge accessible to it.” (Griliches 1992, pp. 34). The importance of spillovers have been emphasized by the recent trends towards open models of innovation (West and Bogers 2017; Gao and Wu, forthcoming). The increasingly porous boundaries of firms, as occurs for example in collaborative innovation, makes spillovers more likely. The importance of spillovers and open innovation for productivity results from the fact, that spillovers can be considered to be valuable inputs. Ignoring them may imply considerable measurement errors for productivity or may alternatively imply tangible traditional inputs falsely appear to have a higher leverage than they have. Also, at the firm-level, productivity may be underestimated for the focal firm if we ignore the productive value of spillovers to other firms.

Starting from the late ’80s, at the macro-level, economists supporting the so-called new growth theories have debated the role of spillovers in explaining productivity growth (see Romer 1986; 1987). Following the theoretical debate, at the micro-level, spillovers have been measured in several ways. Sena (2004) distinguishes three groups of studies. The first group of studies considers spillovers incorporated in ‘intermediate-input’ or patent flows (Nadiri 1993). In this case, knowledge can flow in vertical relationships between firms or in cross-patent citations, respectively. The second group of studies position firms within a technical space and consider firms as users of the pool of R&D expenditure of other firms (Jaffe 1986). Finally, the third group of studies advises that also geographical proximity matters to knowledge flows (Audretsch and Felman 1996): close distance to other innovative firms or research centers favors the flow of knowledge that is not codified, the so-called tacit knowledge. All those studies conclude that R&D spillovers can explain a significant part of productivity growth (Sena 2004). A fourth additional approach not reviewed by Sena (2004) to measuring spillovers and open innovation is to focus on the cooperation with external actors, including firms but also inter-firm alliances (Robin and Schubert 2013; Schubert et al. 2016). The importance of inter-firm spillovers has prompted us to adapt the CDM model to explicitly consider the role of spillovers when relating R&D investments to the firm’s productivity. In doing that, we intend to integrate into the model the external

[3] It is important to distinguish knowledge spillovers from rent spillovers. The later ones “occurs when a firm or consumer purchases R&D incorporated goods or services at prices that do not reflect their user value, because of imperfect price discrimination due to asymmetric information and transaction costs, imperfect appropriability and imitation, or mismeasurement of the true value of the transaction” (Hall et al. 2009). Rent spillovers are considered in the economic literature as a consequence of measurement problems (Griliches 1992). In this study, we will focus on pure knowledge spillovers. Additionally, we will also include direct measures of collaborative agreements. Thus, we will follow both econometric indirect approaches to spillover measurement but also indicator-based approaches.

knowledge capital that a firm can potentially absorb. In looking for this later component, we rely on the extant literature.

Several studies in the economics of innovation literature have looked at the relationship between R&D spillovers and productivity growth. Wieser (2005), in a systematic review of those contributions, has collected the main empirical works estimating the impact of R&D spillovers by including R&D capital in the production function together with labor and capital. The large majority of extant studies have considered a single country (Raut 1995; Antonelli 1994; Harhoff 1998; Jaffe 1986, 1989; Los and Verspagen 2000) or few countries (Branstetter 2001) with particular attention to the United States (Jaffe 1988; 1989; Los and Verspagen 2000). Among the notable exceptions of studies extending their empirical setting to multiple countries, Capron and Cincera (2000) considered a worldwide sample of firms. The stock of knowledge from which a firm can benefit is considered at local and external level or at domestic and foreign level (Wieser 2005).

Griliches' article (1992) meaningfully titled "The search for R&D spillovers" is one of the first comprehensive reviews of the basic model of R&D spillovers and their empirical measurements. Griliches distinguished two types of studies: case studies limited to a particular industry or sector, and larger quantitative studies that consider the overall impact of R&D expenditures outside the focal firm or sector. The first set of studies includes case studies where researchers have an in-depth knowledge of the industry and, at the time of Griliches' review, cases were mainly related to the agricultural field. The quantitative studies are based on a more general econometric model aiming to quantify spillovers.

Looking at the spillover modeling on a production function framework, Griliches proposes a basic model of within-industry spillovers formulated as:

$$Y_i = BX_i^{1-\gamma} K_i^{\gamma} K_a^{\mu} \tag{1}$$

where Y_i is the output of firm i, X_i is the firm i's conventional input and K_i is the firm i's knowledge capital. K_a is the aggregate knowledge of industry a, and the spillover term in the formulation of Equation 1 is μ, the elasticity of the output Y with respect to the knowledge capital K_a . K_a can be considered as a simple sum of the knowledge borrowed by each of the industry j (K_a=$\sum_i K_j$), or a weighted sum under the assumption that the focal firm i firm borrows unequally from other firms (K_a=$\sum_i W_{ij} K_j$). The weight is serves to distance firms from spill-over effects. Consequently proximity is the capability a firm to benefit from spillovers. For instance, the distance in these spillover calculations can be computed on the base of input-output tables that consider the cross-firm/industry purchases (Terleckyj 1980).

The distance can also be considered across industries. For example, firms within the same industry or related industries might benefit greater from each other than firms within unrelated industries. In a more recent review of the literature about spillover measuring, Hall et al. (2009) examined the studies refining the parameters that might be considered in weighting the flow of knowledge across firms and industries. Those parameters go from having common transactions (Terleckyj 1980) to the sharing of personnel (Scherer 1984) or cross-citing patents (Jaffe 1986). The general idea is that a higher frequency of economic transactions, investments, collaboration, or citations between two firms increase the probability that knowledge spills from one firm to the other (Hall et al. 2009). Following O'Mahony and Vecchi (2009), we intend to use a fine-grained industry taxonomy and include dummies for R&D intense sectors under the assumption that firms operating in those sectors are more exposed to exchange of ideas and do benefit from genuine spillovers.

2.4 Servitization

Since the 1990s, manufacturing companies increasingly offer services related to their products. The aim of these product-related service offerings is to achieve a stronger differentiation from competitors and thus ultimately to improve own competitiveness, which in turn should contribute to an increase in sales and profits. In some manufacturing companies, services already generate higher sales than the sale of the physical product itself. Consequently, service components are an essential factor for innovations in manufacturing. Additionally, services offer many new opportunities to generate additional revenues, retain customers and expand and stabilize the volume of orders. This is particularly true for innovative business models based on product-related services. However, whilst delivering services to customers entails many benefits, service provision is still a great challenge for manufacturers (Baines et al. 2009; Brax 2005; Coombs and Miles 2000; Eminli and Bots 2019; Kindström and Kowalkowski 2009; Lay et al. 2010; Lewis and Howard 2009; Matthyssens and Vandenbembt 1998; Miroudot and Cadestin 2017; Vandermerwe and Rada 1988; Wise and Baumgartner 1999).

Furthermore, there is a trend for manufacturing companies to increasingly shifting their focus from pure manufacturing to a combination of manufacturing and services by offering new business models. In addition to offering product-related services, so-called digital business models are increasingly being offered. These business models imply offering integrated solutions of products and services and became common at least among larger manufacturers. Thereby, the implementation of service-based business concepts is a global business trend. Reasons for this development are on the one hand recent changes in the business environment, such as the increasing competitiveness of developing countries, the globalization of markets and the increased awareness and evolution of customer demands, on the other hand, digitalization provides opportunities and dynamic, which makes it difficult to rely exclusively on traditional comeptitive strategies of manufacturers (Biege et al. 2012; Bruhn and Hadwich 2016; Buschak 2014; Lay 2014; Lerch and Gotsch 2015a; Rammer et al. 2018).

While the rising share of services is a central trend in manufacturing, the effect on productivity remains ambiguous. On the one hand, the classical productivity models cannot simply be applied to the provision of services, as they would not take into account essential specificities of services as e.g. the interactive relation to the customer for "producing" a service. On the other hand, the impact of services on the productivity of manufacturing enterprises and thus of the entire economy is a fundamental issue not decisively solved. On the one side, product-related services and new service business models can increase productivity by improving the quality of the services offered and strengthening customer loyalty. On the other side, many service activities have structurally lower labour productivity and many manufacturing firms do not systematically address the issue of measuring and increasing service productivity (Biege et al. 2013; Bruhn and Hadwick 2011; Hoekman and Shepherd 2015; Lerch and Gotsch 2015a; Scerri and Agarwal 2018; Walsh et al. 2016).

There are six general considerations in servitization. These in tern lead to several hypotheses which might be taken into account for adapting the CDM model. The first is the measurement of services in manufacturing. The second concerns the internal measurement of service productivity. The third is understanding the prevalence of hybrid offerings. The fourth is to better understand the digitalization of services. The fifth is to consider the organization of services. The sixth is to properly account for high labor intensity.

First, services in manufacturing are often expected as a "free add-on" when purchasing (new) machines or products. Thus, establishing *services as separately invoiced* additional offers that are not part of the product but an additional offer is quite a sensitive issue. It can be seen as an indication that professional service management is effective in the company, that the costs and benefits of service provision are rationally assessed in the context of the market and with a view to the success of the company, and that service innovation and the qualification of personnel for service provision are strategically considered and managed (Baines 2009; Hepp 2016; Lerch et al. 2013; Rammer et al. 2018). On several occasions, it has been empirically demonstrated that manufacturers directly invoice only parts or even less than half of their product-related services. Instead, these services are included into the product price and thus become not visible to the customer. Even in the case of new products, a new service is often not directly invoiced but rather provided as an additional service added to the new product without being completely included in the price calculation. In the context of fierce competition, the aim is to distinguish it remarkably from competitors' offers. In consequence, the value of these services is often underestimated internally, making it almost impossible to realistically measure this output. This is mainly due to the major drivers of servitization. In manufacturing, servitization often is induced by increasing competition and the resulting interchangeability of products, the resulting price erosion and margin pressure as well as the shortening of product life cycles which force product manufacturers to take a strategic reorientation. In this context, product manufacturers are therefore increasingly turning to services in order to win back lost differentiation potential and build new competitive advantages.

Second, often a lack of attention to the issue of service productivity is reported in the literature about manufacturers. Approaches to *internally measuring and monitoring service productivity* and methods to increase productivity of services are still tasks that need to be tackled directly - especially by smaller manufacturing firms (Biege et al. 2013; Eminli and Bots 2019; Lerch and Gotsch 2015b; Ostrom et al. 2015; Ostrom et al. 2010; Scerri and Agarwal 2018; Walsh et al. 2016). Due the different characteristics of services compared to physical products, service productivity is hard to measure and needs other proxies to assess it. Major differences between goods production and service delivery are linked to the intangible nature of services, the lack of storability, which implies that there is no way for workers to utilize their unused capacity later, and the involvement of the customers in the 'production' of services. Indeed, customers play a critical role in services as they provide input into the service delivery process and places the customer in a dual role of customer and supplier; that is, of co-producer and co-creator of value. The characteristic features of the service make it also clear that the exchange of information and its targeted processing becomes an essential part of value creation. Interactions are a central part of a service production and have a significant impact on its quality. Thus, the consideration of the quality of services perceived by the customer in changing customer experiences and the integration of customers into the service process become essential tasks of an explicit service management. After all, the way information is exchanged as well as the interpersonal contact significantly determines the customer's quality judgement. At the same time, the externalisation of services to customers is often used as a strategy to increase productivity. Likewise, the optimal utilization or the establishment of a balance between the willingness to perform and the actual utilization of the service is of importance for productivity. It is also important to maintain a certain innovation content of services, especially in the area of knowledge-intensive services, whereby it is not so much the direct positive effect on output that is of interest, but rather the degree of innovation that is necessary to maintain competitiveness.

Third, with increasing competition, especially in the manufacturing industry, companies are forced to break new ground in order to conquer a specialized niche and build a loyal customer base. One possibility lies in the design of *hybrid offerings* that closely link production and services. First results show that the most productive firms are those whose business areas provide an additional dimension to differentiate in product markets. By bundling a produced good with a service or vice versa, hybrid firms can offer more valuable products and thus generate higher revenues per employee and generate greater profits for every dollar of sales, as has been shown e.g. in the study by Eminli and Bots (2019). Another way to differentiate from competitors is to entrust partners with the provision of services on their behalf. *Outsourcing external services* that have a direct impact on the company's customers seem to lead to more favorable results than outsourcing internal services. This effect depends on the strategic outsourcing intent, the dependence of the service on the technology and the choice of outsourcing partner (Eggert et al. 2017). In particular in the case of knowledge-intensive services, the *innovative nature of the service* provided should also be taken into account, which, due to the high degree of complexity and the high degree of interaction, offers the possibility of setting oneself apart from competitor (Lerch and Gotsch 2015b).

Fourth, *digitalisation of services* can play a crucial role for the interaction with customers as an essential catalyst for the perception of service quality by the customers (e.g. Bruhn and Hadwich 2016; Hepp 2016; Olderog 2019). By using digital solutions, the interaction with the customer as part of the service production can be largely disconnected in time and space. Customers increasingly communicate via electronic interfaces and thus gain access to their services. Today, the production and innovation of services can mean that service providers rethink, adapt and optimise their technical interfaces to customers and employees and partially replace or at least pre-structure direct communication. At the same time, the demand for digital skills is strongly increasing among customers of these services.

Against this background, it is important to take into consideration that digitalisation of manufacturing is still in the investment phase in most part of manufacturing companies. This implies that new structures still have to be established and new activities have to be developed and adequately equipped with employees. Building new business models based on applications of digital technologies and digitized production remains a complex task. Consequently, the potential of business models is still largely untapped. In addition, although many application possibilities (e.g. networking of development, construction, logistics) are already being exploited, Industry 4.0 applications are still very limited in use for a large proportion of manufacturers. Especially in the B2B sector, the use of digital technologies for small batch sizes, customer-specific offers, or offers for interactive product design are still rather rare today. A large part of digital technologies is still mainly used for automation (Rammer et al. 2018, Lerch and Jäger 2020).

Fifth, *platform use* can also affect productivity (e.g. Lerch et al. 2019). By using or operating digital platforms, companies hope to enter the highly profitable business of digital services based on Big Data and artificial intelligence. Platforms enable transactions that would not be possible, or only to a very limited extent, outside of platforms. In addition to matching costs, digital platforms often reduce information asymmetries. If the benefit of a product or service increases with the number of users, a so-called network effect also comes into play, i.e. the benefit of a product or service increases with the number of users. Besides, platforms might foster the product design process. Consequently, a growing number of platform-based business models are emerging also in established B2B sectors; in manufacturing industry, companies offer their own digital platforms. However, many manufacturers offer only partial solutions via platforms and mainly use platforms for connecting parts of the own company. Most B2B-platforms in manufacturing are mainly used intra-company; being linked through third party platforms is still rare among manufacturers. Consequently, the proportion of cross-company platform connections is still rare.

This reluctance may be due to several challenges faced by producers in using platforms. In particular, transaction platforms are causing a significant increase in the intensity of competition in the traditional markets of industrial companies. In addition, the more anonymous customer contact on platforms also reduces customer loyalty, which in conjunction with global price transparency reduces customer loyalty and makes it more important to master transparent, intelligent product presentations without losing knowledge and know-how. As initial empirical studies show, network or economies of scale are (so far) rarely realised through networking via platforms; even if those manufacturers who consistently use platforms for both product sales and networked services achieve significantly higher revenues with their services, which in turn points to a greater professionalisation of the service business and also suggests that productivity will increase.

Finally, it is often assumed that an increasing share of services is the reason for the decline in productivity simply due to the *high labour intensity* that is caused by lower capital input and less scope for standardisation and rationalisation (e.g. Eminli and Bots 2019; Rammer et al. 2018). In manufacturing, especially the combination of customer-specific products and after-sales/services could have a particularly productivity-reducing effect, since a high level of personnel deployment is necessary for short reaction times and comprehensive services. A main argument is that manufacturing firms have long started to substitute labour with other factors of production, capital and technology, while the service industry is highly dependent on labour. In modern economies, services account for two thirds to three quarters of value added and employment.

3 The econometric model

As the previous chapters showed, the productivity challenge that the European economy faces may be driven by many technology-centered trends, which are not fully understood. Pioneering academic analyses have provided initial evidence on some of the drivers. However, a broad integrative picture is still lacking. This is on the one hand due to the absence of systematic data on some of the core mechanisms. Thus, there is a need for an integrative econometric framework that could help testing the explanations we have discussed in Section 2.1. The point of departure used for the analysis of the innovation-productivity link has been the so-called Crépon-Duguet-Mairesse (CDM) model Crépon et al. 1998), which has since its introduction evolved to the carrying horse of the innovation-to-productivity relationship and on the level of the firm. The CDM-model subdivides the process from innovation input to output into various substages, which can be analysed separately. The reason for its popularity is that develops a multi-stage fine-sliced stage model of how innovative input is transformed into innovative output and finally productivity. Since the secular stagnation hypothesis is precisely based on the argument that changes in the innovation process are the drivers of the productivity slowdown, the CDM model appears to be a highly appropriate econometric modelling choice.

It should be noted, however, that the use of a CDM-type model presents a number of important challenges, which need to be overcome. Because some of the challenges are related to data availability, we will argue that the use of big data approaches (compare Section 4), will contribute to solving these issues to a large degree. The first data-related problems results from the fact of poor proxies on the investment into and use of intangibles at the firm level. Data problems however exist also for servitization as well as spillovers and open innovation. Indeed, the original CDM model and most of its extensions (e.g. Marin 2014; Castellacci 2011; Hall 2011; Griffith et al. 2006; Lööf and Heshmati 2002) have largely used traditional indicators of innovation inputs and outputs, such as R&D expenditures, patents, and information from innovation surveys (e.g. from the Community Innovation Surveys). These measures have been thought to be adequate proxies for innovation processes in the past. However, with the advent of the “intangible economy” (Haskel and Westlake 2018; c.f. also Sichel 2018; Syverson 2017) they may have lost in their ability to capture the central features of innovation. Thus, there is a need to enrich the CDM-model with data, which allow taking explicitly into account the role of intangible capital (see Section 2.2), of spillovers and open innovation (see Section 2.3), and of servitization (see Section 2.4). A further data-related problem, which big-data may solve, is the empirical gap between the firm-level focus of the CDM-model and the desired macro-level perspective on the productivity paradox. Indeed, because most applications of the CDM-model have relied on Community Innovation Survey data, there is little possibility to generalize the findings directly to the macroeconomic level. The reason is that the CIS-samples are typically quite small compared to the population of the firms in each country. Even when using weighted regressions, it remains highly speculative how causal effects identified on the basis of the CIS-sample translate into productivity phenomena observed at the macro-level. Thus, in order to develop a closer link between micro- and macroeconomic results, there is a huge need to gather information on a greater share of the firms of which the relevant population consists. As we will see in particular in Section 4, the use of big-data approaches in combination with data from structured databases (such as ORBIS or the R&D scoreboard) can greatly improve on these data-related limitations. Thus, a first goal of an extended CDM-type of model is to unpack and extend the knowledge-component in the original CDM-model (Crépon et al. 1998) by including not only traditional measures of innovation input and output (such as R&D and patents) but also to include investments into intangibles. The second goal is to establish a closer link between micro and macro-level evidence by gathering information on a larger share of the population under scrutiny.

Beyond pure limitations in data availability, there are however also conceptual shortcomings in the original CDM-type of models. In particular, Haskel and Westlake (2018) argued that a characteristic feature of intangible capital is its ability to generate spillovers. The authors, in fact, speculate that the declines in productivity growth may indeed be the result of the decreasing spillovers associated with intangibles. Spillovers have, however, not played a central role in CDM models, which have focused almost exclusively on the role of the focal firm's investment on its own output and productivity. Thus, there is a need to model spillovers into the CDM-approach (see also Section 2.3). Moreover, Haskel and Westlake (2018) make a convincing case that the ability to profit from investment into intangibles differs substantially by firm. Moreover, the increasingly networked character of innovation blurs the boundaries of firm innovation. Thus, an extended CDM-model will also need to take firm heterogeneity explicitly into account. Including spillovers and firm heterogeneity in an extended CDM model is therefore our third and fourth objective.

Before we explain, how we intend to develop the CDM-model further, we will present a sketch of its key equations now.[4] In the first stage, Crépon et al. (1998) consider the input stage, which determines whether a firm will invest in R&D.

$$g^* = x_0 b_0 + u_0 \tag{2}$$

$$k^* = x_1 b_1 + u_1 \tag{3}$$

where $g^*$is a latent industry threshold determining whether to invest in R&D. k^* is the R&D intensity, where $k^* = k$ if $g^* > 0$. The x-vectors contain key explanatory and control variables that affect the firms' likelihood to invest into R&D as well as the overall level of investment. These may include but are not limited to firm size, sector dummies, labour and physical capital input, export orientation, or characteristics of the competition.

On the next stage, we have an innovation function, which relates the innovation input of the last stage to the innovation output. Crépon measured this in two equations by patents and share of turnover due to innovation.

$$p = exp(\alpha_1 k^* + x_2 b_2 + u_2) \tag{4}$$

$$s = \alpha_2 k^* + x_2 b_3 + u_3 \tag{5}$$

In the final step, Crépon et al. (1998) use the innovation outcome to explain firm-level productivity.

$$q = \alpha_2 ln(p) + x_3 b_4 + u_4 \tag{6}$$

$$q = \alpha_3 s + x_3 b_5 + u_5 \tag{7}$$

Using data from the CIS, it is principally possible to estimate Eq. (2)-(7) consistently with different econometric approaches, depending on the assumptions one is willing to make about the cross-correlations between the

[4] For expositional clarity, the mathematical symbols are not exact reproductions of the Crepon et al. (1998).

error-terms (compare Wooldridge 2002). As we can see, once we have estimated all coefficients in the model, we get a very detailed picture of how investment into R&D trickles down to innovation output and eventually to productivity. Because all equations are linked to each other in a triangular fashion, we are able to estimate not only the within equation effects of a focal explanatory variable, but also how it indirectly affects later stages.

As argued above, the scientific literature on the sources of the productivity decline suggests that the focus on R&D only may be too simplistics in an age where intangible investments are on the rise. Moreover, we need to take into account also spillovers from other firms. Thus, Eqs. (2)-(7) need to be extended. Assume that we have a measure of focal firm's investment into intangibles i and measure $\underline{i}$ of the sectors investment into intangibles (compare also the more detailed information on how to proxy spillovers in Eq. (1)). As before, we can define the investment stage as follows:

$$g^* = x_0 b_0 + \gamma_0 \underline{i} + u_0 \tag{8}$$

$$(k+i)^* = x_1 b_1 + \gamma_1 \underline{i} + u_1 \tag{9}$$

There are two central differences. First, the sector threshold to expend resources on either R&D and or intangibles now depends on the sector investment of intangibles, too, implying that we can measure the role of spillovers. Second, instead of focusing only on R&D, we now explicitly look at both R&D and intangible investment, where

$$(k+i)^* = k + i \text{ if } g^* > 0.$$

We also make some additional adjustments. Crépon et al. (1998) have relied on the use of the share of turnover with new products. The share of turnover with new products is indeed a widely used and easily accessible key figure coming from the CIS-surveys, but is increasingly criticized because of its unclear meaning. A number of authors have therefore made attempts to measure innovation output by counting actual innovations also taking into account their specific characteristics such as their inventive height. This approach has indeed a long-history and was first introduced by the SAPPHO-project (compare Rothwell et al. 1974). A good recent example of this approach is the work by Kander et al. (2019), who identified individual product innovations by scrutinizing announcements in relevant industry journals. Despite its merits relating to the precise identification of actual product innovations, the approach has come out of fashion because of the huge manual investments. For the last thirty years, the measurement of innovation outcomes thus was based largely on patents or on survey-information. While we believe that patents are still a good measure of the inventive stage in some industries, the use of big data approaches allows for an identification of actual innovations on a broader scale. Our data approach allows us to identify on the one hand innovations introduced by the firm as well as to distinguish these innovations between imitative innovations (ii) and genuine market innovations (mi). Taking these measures as alternatives and taking into account the role of spillovers and intangibles, a generic version of the innovation stage can be rewritten as follows:

$$p = exp(\alpha_1 (k+i)^* + x_2 b_2 + \gamma_2 \underline{i} + u_2) \tag{10}$$

$$ii/mi = \alpha_2 (k+i)^* + x_2 b_3 + \gamma_3 \underline{i} + u_3 \tag{11}$$

Finally, the productivity stage is:

$$q = \alpha_2 ln(p) + x_3 b_4 + \gamma_4 \underline{i} + u_4 \tag{12}$$

$$q = \alpha_3 ii/mi + x_3 b_5 + \gamma_5 \underline{i} + u_5 \tag{13}$$

We note, that the extended CDM-model proposed in Eqs. (8)-(13) can be further refined in a number of ways. Most obviously, we can separate the influence of R&D expenditures and investments into intangibles. One way to do that would be to add separate investment equations for each type of investment in stage 1. Furthermore, we can allow that there are spillovers also from R&D and not only intangible investments. That could be implemented by adding a further regressor $\underline{k}$ measuring the sector R&D expenditures to Eqs. (8)-(13). As discussed in Section 2.3, there is also some room to experiment with different kinds of proximity weights. In addition, because the final database will be a panel dataset, we will be able to analyze how coefficients change over time. We can therefore, amongst many other things, directly provide an empirical test of whether Haskel's and Westlakes's (2018) hypothesis of declining spillovers from intangibles is correct.

Because we will work only with specific sectors, our results will probably not allow to obtain macroeconomic estimations. However, we are still able to address the question of the microfoundations of the productivity paradox at the level of the firm.

4 Description of the data

Against the background of the econometric model described in chapter 3 and based on the literature review presented in chapter 2, several propositions to capture intangibles (Table 1), open innovation (Table 2), servitization (Table 3), digitalization (Table 4), and innovation and knowledge generation (Table 5) by resorting to big data approaches as well as large structured data is provided in addition to the list of key figures (see Table 6) that is needed to estimate the basic CDM model.

In principle, two major data sources will be mainly used. On the one hand, data captured by the ORBIS database, a commercial database of companies, covers the universe of European firms which are of interest and consists of standard key business indicators. On the other hand, data made available by the companies on their websites will be explored using web scraping and further big data approaches to structure unstructured data as e.g. by topic modelling. Additionally, classic structured databases as patent databases, databases on scientific publications, and trademark databases provide a valuable source to capture specific aspects of innovation and knowledge organisation.

To frame the exploitation of unstructured online data, the companies listed in the ORBIS database define the population on which data will be searched at and derived from company websites. ORBIS data are the population frame to assess the data availability for each indicator. Thus, by collecting these data we can additionally document the test of probable biases in online representation and data quality. Of course, the coverage of ORBIS will be crosschecked with basic statistical data.

The following Tables 1 to 6 provide a structured overview of the selected indicators. These lists are derived from literature review and conceptualizing the proposed ideas and consist of an initial proposal of which variables may be useful for the analyses. Further evaluation and testing will be needed before including them into the model - in particular for the variables resulting from the exploitation of big data. For each indicator, data quality will be assessed. Table 1 to Table 5 are organized by topic; each provides in column 1 the potential construct to be covered, in column 2 a short description of the indicator itself, in column 3 the probable source, and finally in column 4 a reference to studies which already used (partially) this indicator.

Table 1: Intangibles

Topic	Indicator	Source[1]	Analyzed already/refer to
Intangible assets	Activated value of intangibles resp. investment expenditures	O	(Shakina and Barajas 2016, Chen et al. 2016, Webster and Jensen 2006, Edquist 2011, Malik et al. 2014, Thum-Thysen et al. 2019, Yang and Shi 2018, Yang et al. 2018, Jona-Lasinio and Meliciani 2019, Addison and Wagner 1994, Gandin and Cozza 2019, Nisar 2006, O'Mahony 2012, Mishra and Ewing 2020, Arrighetti et al. 2014; 2015, Niebel et al. 2017, Miyagawa and Hisa 2013)
Capital assets	Investments or stock	O	(Castellani et al. 2010)
Organisation	Share of number of employees per unit	CW	(Popescu 2019, Lobova et al. 2019)
	# of divisions (production lines, markets, ...)	CW	(Verbic and Polanec 2014, Tatari and Skibniewski 2011)
	# of departments	CW	(Verbic and Polanec 2014, Tatari and Skibniewski 2011)
	Changes in the divisions/departments, dummy	CW	(Bin Ab Hamid 2015, Shahiduzzaman et al. 2018)
Top management	# of top-managers	O	(Shahiduzzaman et al. 2018, Nemlioglu and Mallick 2017)
Diversity of top management	Nationality of Top Management [Shares by countries/country groups]	O	(Marcin 2008, Gutierrez and Philippon 2017)
	Share females	O	(Migliaccio 2019)
	Shares by age groups	O	(Li et al. 2011)
Educational field of CEO	Dummies for education fields	CW	(Corrado et al. 2017b, Hagsten and Sabadash 2017, O'Mahony 2012, Steingrimsson et al. 2017)
Gender of CEO	Dummy	CW	(Migliaccio 2019)
Educational field of Management	Shares by education fields	O	(Palmon and Yezegel 2012)
Educational diversity of workforce	Dummies for education fields	CW	(Aggarwala et al. 2019)
Training/education costs	Share of costs based on turn-over	O	(O'Mahony 2012, Li et al. 2011, Zambrano et al. 2012, Chen et al. 2016, Saunders and Brynjolfsson 2016, Phusavat et al. 2011, Ballot et al. 2001, O'Mahony 2012, Goodridge et al. 2017, Migliaccio 2019, Corrado et al. 2017a, Ciriaci 2017, Lopez-Garcia et al. 2013, Dal Borgo et al. 2013, Ballot et al. 2006, Berk and Kase 2010)
Career / work force incentives	Specific topics identified based on topic analyses based on extracted career information	CW	(Tomlinson 1999, Schiller and Diez 2010, Mishra and Ewing 2020)
Mission/vision	Specific topics identified based on topic analyses within extracted mission statements	CW	(Warner et al. 2007, Shakina and Barajas 2016)
Certificates, certified standards	# of certifications by type [e.g. ISO, C-MARK - regarding Innovation, labour forces]	CW	(Quintino et al. 2012, Richnak et al. 2016, Testa et al. 2011, Iraldo et al. 2009)
	diversity of certification - which fields addressed	CW	-

Topic	Indicator	Source[1]	Analyzed already/refer to
Customer structure	# of customers;	CW	(Tuli et al. 2010, Gronroos and Helle 2012, de Castro et al. 2009a; 2009b, Scerri and Agarwal 2018, Bontempi and Mairesse 2015, Banerjee 2000)
	Consumer/industry addressed	CW	(Tuli et al. 2010, Gronroos and Helle 2012, de Castro et al. 2009a; 2009b, Scerri and Agarwal 2018, Bontempi and Mairesse 2015, Banerjee 2000)
	Technology fields are addressed? by services, by production	CW	(Färber 2019, Wang et al. 2019)
Product diversification	# of Product description URLs	CW	-
Internationalization	# of languages on website	CW	(Filatotchev and Piesse 2009, Fukao 2013)
Geographical innovation market	Geographical information in product announcements	CW	(Harris 2011, Dettori et al. 2012)
talents, work force relation	Announcements for recruitees	CW (Career part)	(Wang et al. 2003)

Source: Compiled by Authors. Note: 1) Appreviation O stands for ORBIS database, and CW for Company websites.

Table 2: Open Innovation

Topic	Indicator	Source[1]	Analyzed already/refer to
Collaboration with other organisation	# of other companies referenced	CW	(Dyer and Singh 1998, Cohen and Levinthal 1990, Simonin 1997)
	# of reported collaboration relationships by type of organization	CW	(Simonin, B.L. 1997)
Alliances, Joint venture	# of announcements	CW	(Chang et al. 2013)
Collaboration with R&D organisation	R&D institutions, Universities	CW	(Robin and Schubert 2013)
Collaboration with researchers	# of persons (via)	CW	(Robin and Schubert 2013)

Source: Compiled by Authors. Note: 1) Appreviation O stands for ORBIS database, and CW for Company websites.

Table 3: Servitization

Topic	Indicator	Source[1]	Analyzed already/refer to
Products/Services with software component	Dummy	CW (product announcement)	(Nwankpa and Roumani 2016, Dehning and Richardson 2002)
New services	# of new services	CW	(Lay 2014, Lay et al. 2010, Biege et al. 2012
Transformation of business models	Services offered? Dummy (.. as Industrial company)	CW	(Eminli and Bots 2019)
	Additionally, hardware/products offered? Dummy (.. as Service company)	CW	(Eminli and Bots 2019)
Hybrid business solutions	Nominal - servitized manufacturer - manufacturing service provider	CW; O [text based classification]	(Eminli and Bots 2019)

Source: Compiled by Authors. Note: 1) Abbreviation O stands for ORBIS database, and CW for Company websites.

Table 4: Digitalization

Topic	Indicator	Source[1]	Analyzed already/refer to
Offering digital business models	Dummy [yes/no]	CW	(Lerch et al. 2019, Lerch and Gotsch 2015a)
Investment for IT	Investments or expenditures	O	(Lee et al. 2016)
IT security efforts	# of certificates of security	CW	(Hsu et al. 2016)
B2B platforms	Nominal - used - offered	CW	(Lerch et al. 2019)

Source: Compiled by Authors. Note: 1) Abbreviation O stands for ORBIS database, and CW for Company websites.

Table 5: Innovation & knowledge generation

Topic	Indicator	Source[1]
Developing prototypes	# of prototypes	CW
Proof of concetps	# of proof of concepts	CW
Status product innovator	Dummy	CW
New products by degree of novelty (market novelties vs. other novelties)	# new products by type	CW
New processes introduced	# of new processes feature for the new product	CW
	as certificates of processes as KANBAN etc.	CW
New organisational structure, Re-organisation processes	Announcements on websites	CW
Patents	# of patents	PATSTAT
Academic patents	# of academic patents	PATSTAT-Scopus-match

Source: Compiled by Authors. Note: 1) Abbreviation O stands for ORBIS database, and CW for Company websites.

Table 6: Basic key figures

Topic	Indicator	Source[1]
Financial information	EBIT or EBITDA	O
	Sales	O
	Input share	O
	Value added	O
	Investments or stock	O
Firm size	Number of employees	O
Stability of company	Age of organisation	O
Exports	Exports	O
Sector	NACE near classification (grouped)	O
Market aimed to	To what market is delivered/sold	CW
Low tech/high tech	Dummies	O [text based classification]
R&D	R&D expenditures	O
Location	Postal code	O

Source: Compiled by Authors. Note: 1) Abbreviation O stands for ORBIS database, and CW for Company websites.

5 Summary

In this report, we outlayed the basis for the econometric estimation relation to the microfoundations of the productivity paradox at the level of the firm. We have reviewed the literature and have highlighted the importance of technology-centered explanations of the productivity paradox. We have also argued that trends towards intangibles, spillovers/open innovation, and servitization can contribute to shed light on the productivity paradox, potentially, in parts explaining it. We exemplarily highted some of the mechanisms, by which these trends may affect productivity. So far, it is been difficult to put these mechanisms to test because of problems in data availability. Our big data approach, we argue, will provide valuable ways forward in this respect. In particular, we have explained which data we will attempt to collect providing a detailed plan whether the data will come from structured sources like ORBIS or PATSTAT or unstructured sources like company websites. Building on the promise of this unique data source coming from combining structured and unstructured data sources, we proposed an extended CDM-type of model, which will allow us testing inasmuch intangibles, spillovers/open innovation, and servitization affect productivity at the level of the firm.

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